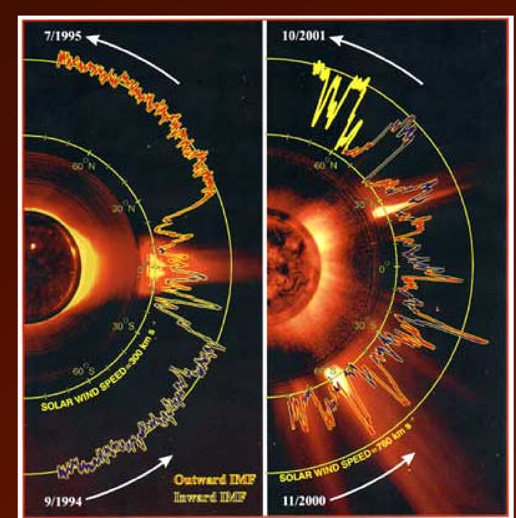
Solar Probe

Trajectory Analysis and Solar Gravitational Modeling

2003 NASA Academy Individual Project
NASA Goddard Space Flight Center
Research Associate: Joni R. Jorgensen
Principal Investigator: Dr. Ed Sittler, Code 692

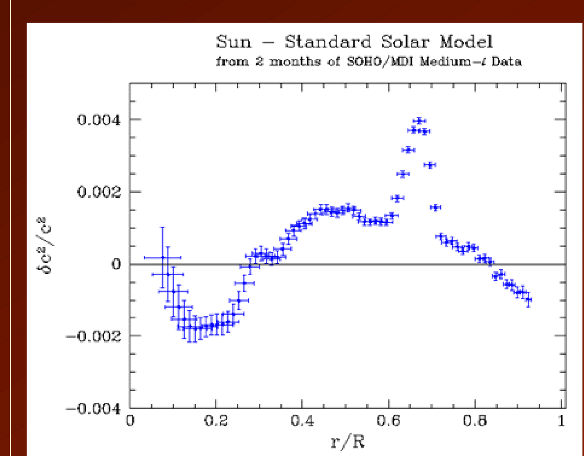
Background Information

Solar Probe is an ambitious project that is designed to study several solar characteristics and processes:



Data obtained from Ulysses at solar maximum (right) and solar minimum (left)

- Solar Wind
  - Origins and Sources
  - Acceleration Processes
  - Space Weather
  - Changes with Solar Cycle
  - Coronal Heating
  - Corona Density Configuration

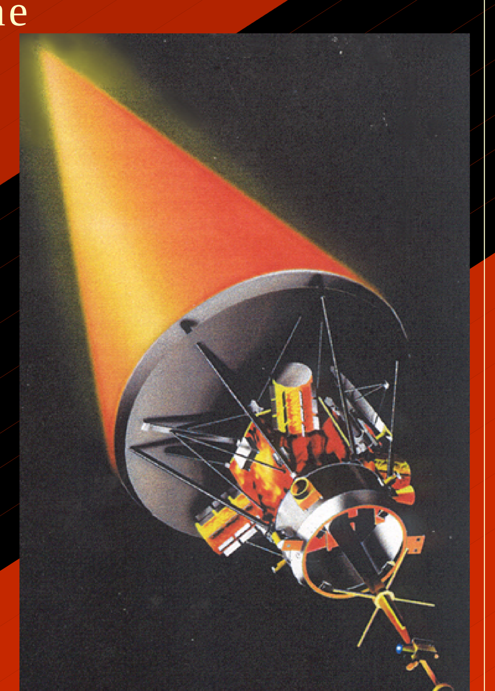


Sound speed variation with solar radius

- Verification of helioseismology probing of Sun's interior: Radial variation of mass density
- Time dilatation and general relativity: Orbit will precess 205 arcsec/century (compared with Mercury's orbit which precesses 43 arcsec/century).

In order to study these phenomenon **Solar Probe** is designed to make several passes very close to the sun (ultimately four solar radii from the sun's center). This presents many challenges:

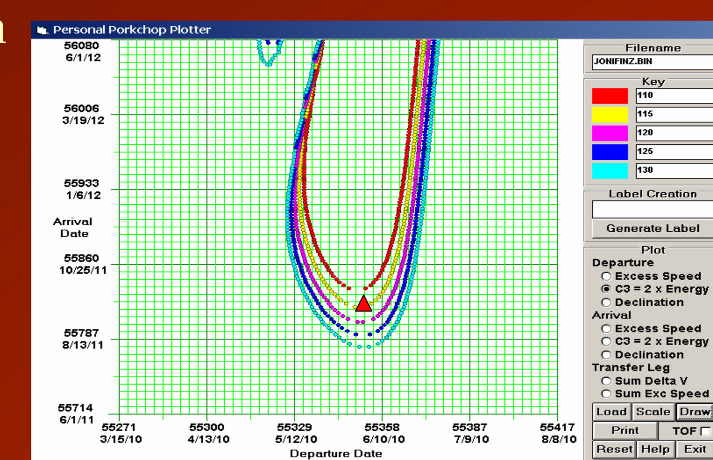
- Spacecraft Protection
  - Verification of spacecraft thermal model near the Sun
  - Shielding delicate instruments from dust and radiation
- Amount of Scientific Data Attainable
  - Large orbital period
  - Small solar encounter time
- Communications
  - Angle requirements between the spacecraft and the earth during solar encounters (for Doppler shift effects)
  - Direct link to Earth to ensure data collection
  - X-Band and Ka-Band required



Individual Contribution

Verification of APL Study data

- Launch Dates
- Launch Energy
- Declination
- Launch Vehicle Selection
- General Trajectory



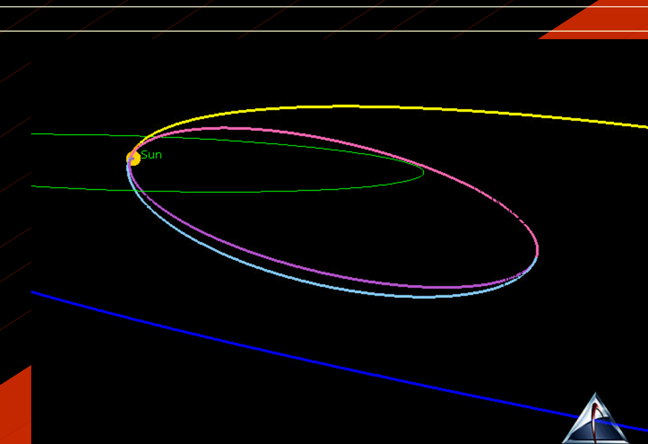
Plot of departure and arrival dates at Jupiter for various launch energy

Plot of the payload mass for various launch energies for the Atlas V and Delta IV Heavy (both with Star 48B third stage)

The APL study used an Atlas V launch vehicle. Due to additional mass for maneuvers, a Delta IV Heavy is required for this mission.

Final Orbit Parameters

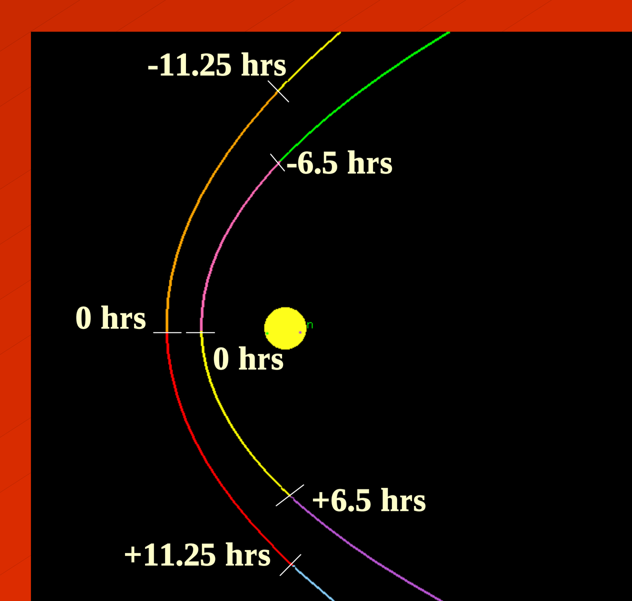
Period	0.994 year
Inclination	89.993 degs
R_a	1.976 AU
R_p	4.00 R_S
Angle between spacecraft and earth at perihelion	85.081 degs



Graphical representation of spacecraft trajectory around the sun

Trajectory Timeline

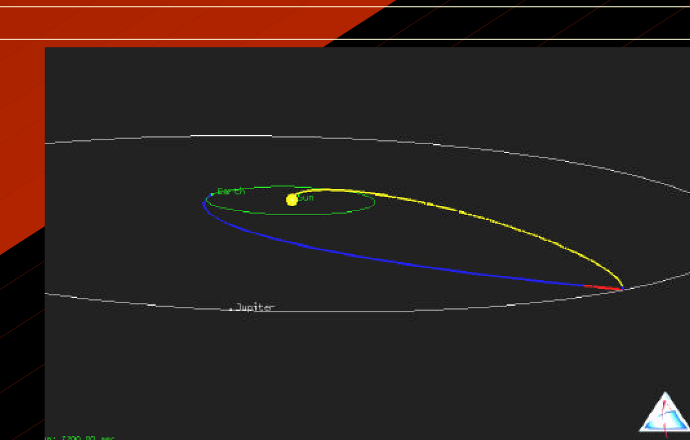
- May 26, 2010: Launch into Earth orbit (Delta IV)
- 24 minutes later: Leave Earth orbit, bound for Jupiter
- Sept. 3, 2011: Jupiter Swing By
- Jul 18, 2013: Arrival at Perihelion - Conduct first burn to reduce period to 1 year
- Jan 17, 2014: Conduct second burn at aphelion to reach R_p=4.0R_S
- Jul 17, 2014: Second perihelion pass at four solar radii



Close up of the Solar Encounter for a perihelion radius of 5.66 R_S (outer) and 4.0R_S (inner). Decreasing the perihelion radius cuts the solar encounter by almost 9 ½ hours.

Initial Orbit Analysis Goals:

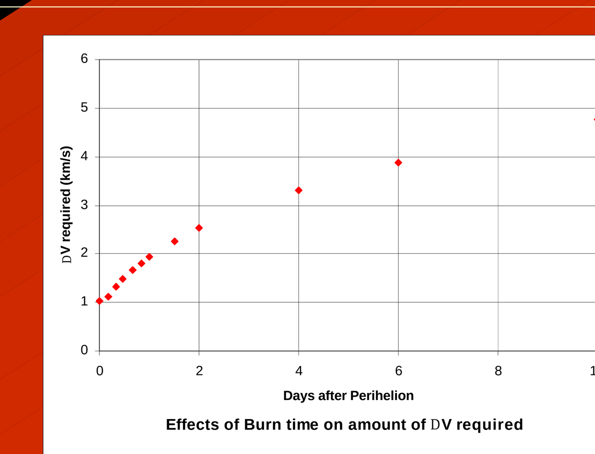
- 5.66 perihelion radius
- 90 degree inclination
- Achieving correct alignment between the spacecraft and the Earth



Plot of the initial orbit conducted to achieve 5.66R_S perihelion and 90 degree inclination

Maneuver Analysis

- Burn at (or close to) perihelion to achieve a period of one year
  - Fuel Efficiency versus Spacecraft data collecting capabilities
- Burn at aphelion (if thermal models are accurate) to attain a perihelion radius of 4.0 solar radii



Plot of time after perihelion and velocity change required to achieve a period of 1 year

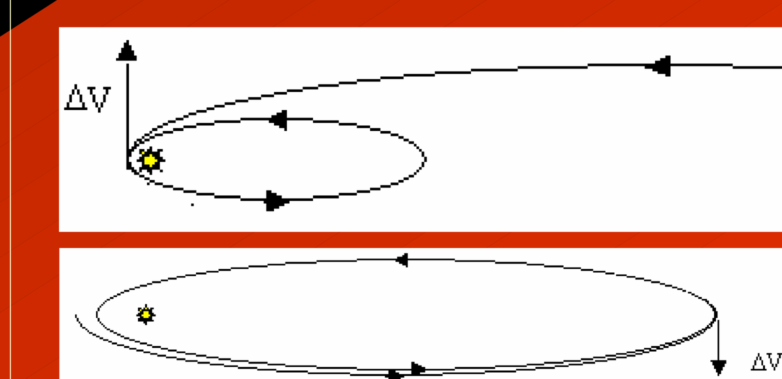


Diagram of each burn - The burn at perihelion (top) will reduce the period to 1 year. The burn at aphelion (bottom) will reduce the perihelion radius to 4.0 solar radii.

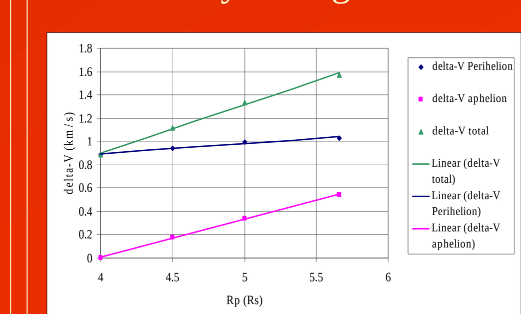
- Reducing period to 1 year
  - Burn location: perihelion
  - ΔV required: 1.0299 km/s
- Reducing R_p to 4.0 R_S
  - Burn location: aphelion
  - ΔV required: 0.5430 km/s

Fuel Requirements

- Burns (I_{sp}=230 s): $M_{fuel}=M_{dry}(e^{\Delta V/(I_{sp}*g)}-1)$
  =655.17 kgs
- Attitude Control: 6 kgs
- Margin (10 percent): 66.12 kgs
- **TOTAL: 727.29 kgs**

The mass allotted for fuel was 316 kg. This is significantly smaller than the amount of fuel required for the mission. Several options will be investigated to try to limit the propellant required or decrease the mass of the spacecraft.

Decreasing the initial perihelion radius will cause the velocity change to reach an orbit of one year to decrease. This is one method that could be used to decrease the propellant required; however, the margin for the thermal model would be compromised.



Change in ΔV when different initial perihelion radii

Benefits Over Original Trajectory

- Shorter orbit period - Increases the number of solar encounters from 2 to 5 for the same mission duration.
- Reduced mission risk: Thermal loads at 5.66 R_S are a factor 2 lower than the loads at 4.0 R_S.

Conclusions and Future Work

- An orbital period of one year with a perihelion radius of four solar radii was achieved, but a large amount of propellant is required.
  - Investigate ways to minimize spacecraft or fuel mass
    - Minimizing mass of certain components
    - Using a bipropellant instead of a monopropellant
  - Decrease the launch energy required, which would increase the mass available
  - Examine methods to limit ΔV required
    - Decrease the initial perihelion radius
    - Increase the orbit period
- Placing the first maneuver such that there is a compromise between burn efficiency and scientific benefit
  - Conclusion: First maneuver must occur at perihelion because of fuel requirements
- Examine having an angle of 60 or 120 degrees between the spacecraft and the earth during solar encounters
  - Allow for measurements of doppler effects so that gravity calculations can be made.
- Modeling gravity field of the sun (as to not treat the sun as a point mass)
  - See the effects of these models on the spacecraft's trajectory

References

APL, *Solar Probe: An Engineering Study*; 2002

Satellite Tool Kit 4.3, Analytical Graphics, 2002

Brown, Charles D., Spacecraft Mission Design Second Edition, American Institute of Aeronautics and Astronautics, Inc.; 1998

Sound speed Plot, http://soi.stanford.edu/results/sspeed.html

Solar max/min figure http://spaceflightnow.com/news/n0110/16solarwind/ulysses.jpg

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